ECSE 426 - Microprocessor Systems
Final Project

Group 4
Matthew Lesko
Marcel Morin
Fabrice Normandin
Harley Wiltzer (260690006)

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1 Problem Statement

This text presents the design of a system whose ultimate goal is to gather data using the peripherals of a microcontroller and publish this data to a webserver via a chain of different communication media. From the user's perspective, the only setup required involves installing an Android application (designed for the purposes of this project) and launching a web server to collect the recorded data. After the Android device has paired with the Nucleo microcontroller, the data recorded from the accelerometer or microphone attached to the STM32F407 Discovery board will be transmitted automatically to the webserver, where the data may be visualized numerically and with pictorial support. If the data being sent is a microphone recording, the web server will perform *speech recognition* to parse a number n from the recorded audio, which will be communicated all the way back to the Discovery board, causing an LED to blink n times.

Given the reduced amount of resources usually present in microcontrollers, several devices were required to work in tandem in order to create a pipline from the Discovery board to the Internet. The Discovery board, while having access to an accelerometer and an ADC for reading microphone data, has no resources for communicating over Bluetooth or HTTP. Instead, it may communicated via a wired connection to the Nucleo board that is fitted with a Bluetooth Low Energy (BLE) transmitter. Given that the Nucleo has no WiFi capabilities, it communicates data over BLE to an Android application, which may then tunnel the data over HTTP to the web server. Thus, in order to communicate sensor data from the Discovery board all the way to the web server, three distinct communication protocols are used (UART, BLE, HTTP), each having their own unique quirks and *impedimentum*. A major challenge of the design of this system revolved around the design of how to encapsulate data to be sent, and how to ensure the timing between transmitters and receivers was appropriate.

Furthermore, given the plethora of devices responsible for the transmission of data in this system, it was necessary to implement four distinct software components across three different technologies. As will be described further in this report, both the Discovery and Nucleo board required independent embedded-C programs. Furthermore, to bridge the gap between the microcontrollers and the web application, an Android app was devised and implemented in Java. Finally, the web application prompted the design of a RESTful API as well as a fancy interface for displaying the data it received. This was achieved mainly with the Python language and some of its excellent libraries.

Finally, another design challenge was that of speech recognition. Although a custom Convolutional Neural Network was initially designed for this task, the amount of time that would have been required to train it properly would have severely hindered progress on the rest of the project. Therefore, the speech recognition feature was outsourced to a Google Speech API.

The remainder of this text will describe how the system was designed, and will discuss the various challenges were experienced as well as how they were resolved. Ultimately, the system proposed in this paper is meant to show how embedded systems can communicate with each other, as well as how they may communicate over the vast Internet. Thus, the proposed system exhibits the *Internet of Things*, a field and concept that has been growing tremendously and is projected to grow into a market worth $7.1 trillion by the year 2020[1].

The legendary philosopher John Milton once said "give me the liberty to know, to utter, and to argue freely according to conscience, above all liberties"[2]. The Internet of Things and the design proposed in this paper ultimately recognize microcontrollers as entities capable of knowing, uttering, and arguing, which was, above all else, demonstrated by the proposed system. The Internet of Things revolution, therefore, shall eventually bring the "Inter-computational Covenant on Civil and Political Rights", allowing all devices to communicate equally to advance society. The authors hope that the results demonstrated in this text show promise in the evolution and advancements in the freedom of device-expression.

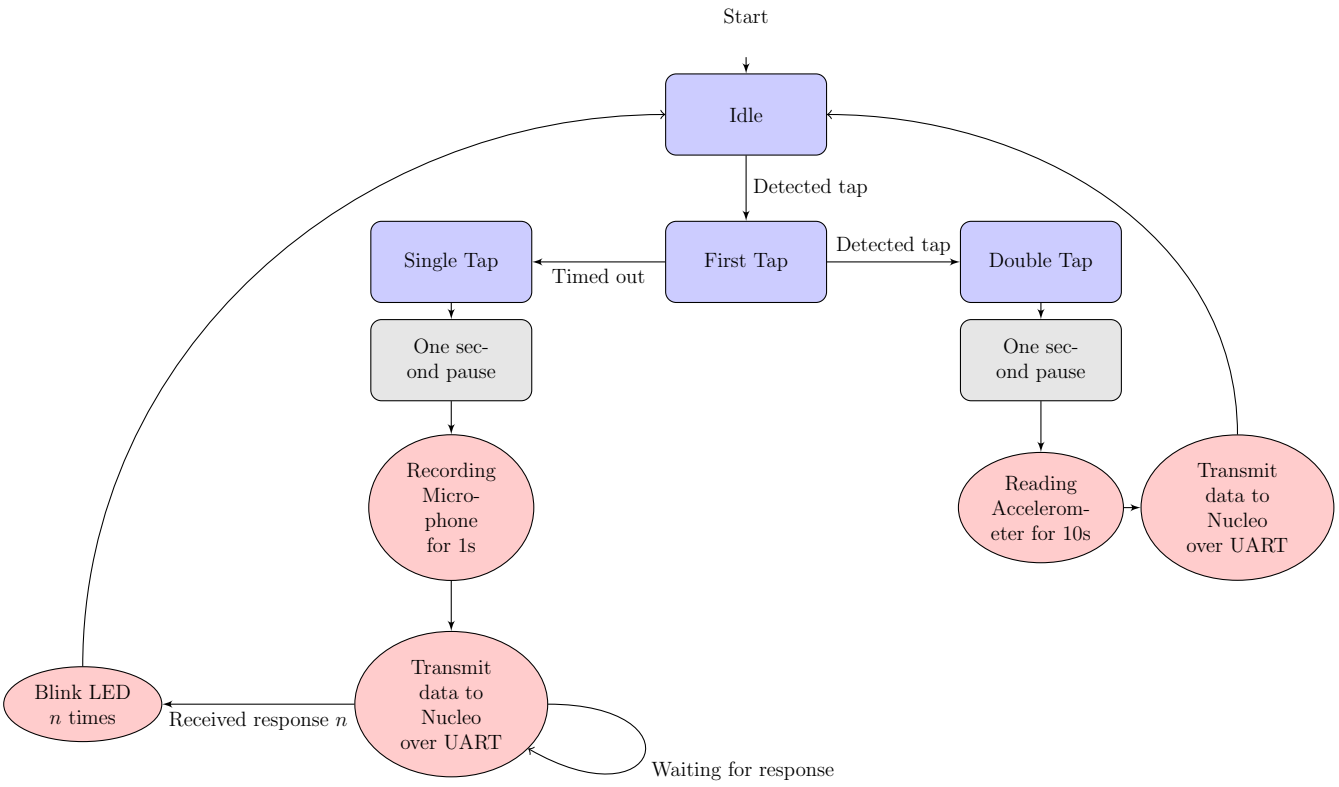
2 Implementation

2.1 The Beginning of the Pipeline: Handling the STM32 Discovery Board

The STM32F407 Discovery Board is the microcontroller that the user interacts with. As discussed previously, this board is responsible for gathering accelerometer and microphone data to send through the pipeline. Figure 1 demonstrates the Finite State Machine that the Discovery Board adheres to.

The system starts in the Idle state, where it waits for user input in the form of taps on the

Figure 1: FSM on the Discovery Board



board itself. The taps are detected by accelerometer readings polled at 100Hz over 500ms intervals, when an accelerometer reading on the z axis surpasses the average reading over the window by a certain threshold. In order to filter out noisy accelerometer readings, an exponential moving average filter is applied, which filters as follows:

$$\hat{z}_t = \alpha z_t + (1 - \alpha)\hat{z}_{t-1}, \alpha \in (0, 1] \tag{1}$$

where z_t is the tth accelerometer reading, and $\hat{z}$ is tth output of the filter. The parameter α was chosen through testing, and it represents how "smooth" the filter output should be.

When a tap is detected, the system enters the First Tap state, and the green LED is illuminated for visual feedback, so the user can gauge how rapidly to make a double tap. If no tap tap is detected in the next 500ms window, the system enters the Single Tap state (denoting that it has detected only a single tap) and the blue LED is illuminated, and otherwise, it enters the Double Tap state where the orange LED is illuminated. These states ultimately determine which data to record, and how the rest of the system proceeds. In either case, there is a one second delay after the transition to these states to allow the user to prepare for the recording.

2.1.1 Sending Microphone Data

In the event that the system enters the Single Tap state, after the aforementioned one second grace period, the machine will begin to record data from the microphone. This data is sampled at 10kHz by the onboard analog to digital converter (ADC) for 1 second using direct memory access (DMA). During this recording period, the Discovery Board's red LED will be blinking. When the blinking stops, the recording has finished. In order to retain high audio quality, the ADC converts samples to 12-bit integers. Since the FSM is not in use during the recording period, it begins to wait on a signal before continuing. This effectively prohibits the FSM from being scheduled by the CPU until the signal is set. Once the DMA buffer is filled with ADC readings, a callback function is triggered, which in turn sets the signal allowing the FSM to resume.

After receiving the signal from the ADC DMA callback, the FSM can once again be scheduled. However, before sending the microphone data to the Nucleo board, it is desired to *compress* the data returned by the DMA process. Since DMA buffers contain 32-bit words and ADC samples are only 12 bits wide, it is desirable to *squash* the data in the DMA buffer into 16-bit integers. This was done by an elegant `squash` algorithm, that performs this operation in place. This halves the amount of bytes required to send to the Nucleo board over UART.

With the compressed data ready, the Discovery Board asserts a `Data Interrupt` GPIO pin, which is directly connected to the Nucleo Board. This will trigger an interrupt on the Nucleo, essentially informing it that it should be ready to receive a UART transmission. Furthermore, it asserts a `Mic Data` GPIO pin, also connected directly to the Nucleo Board, which tells the Nucleo that it is about to receive microphone data. Then, the Discovery board begins transmitting the microphone data over UART.

Once the UART transmission is complete, the Discovery Board must wait from a response indicating how many times its LED should blink as indicated by the microphone reading. Since the amount of time necessary to receive the response is relatively enormous, it is undesirable for the Discovery Board to poll for UART responses. Thus, it initiates a UART Receive in Interrupt Mode, which will trigger an interrupt when the desired byte is received from the Nucleo Board. Meanwhile, the FSM waits on another signal in order to prevent it from being scheduled by the CPU. This signal is set when the UART Receive callback is triggered.

Upon receiving a response from the Nucleo Board, the discovery extracts a number $n \in \{0, 1, \ldots, 9\}$ from its receive buffer. Then, the blue LED will blink n times, indicated the number that was recognized from the initial microphone reading. After the LED has finished blinking, the system returns to the Idle state, ready to start all over again. At this stage, no LED's should be

illuminated.

2.1.2 Sending Accelerometer Data

In the event that the system enters the Double Tap state, after the aforementioned one second grace period, the machine will begin to record accelerometer readings at 100Hz for 10 seconds. As in the case of the microphone recording session, the red LED will blink for the duration of the accelerometer recording. In order to reduce the amount of data that will be sent over UART (and later, over BLE), the Discovery Board converts each accelerometer reading (x_i, y_i, z_i) into pairs (p_i, r_i), where p_i and r_i are the corresponding pitch and roll measurements, respectively. Then, rather than sending $3 * 10000 = 30000$ floating point numbers, only $2 * 10000 = 20000$ floats must be sent.

Note that in contrast to the case of the microphone data, where it was desired to compress the readings into 16-bit integers, the accelerometer data should be kept at pairs of 32-bit floats to retain enough precision. However, before transmitting the data it is passed through an exponential moving average filter. However, this filter uses a less smooth α parameter as that which was used for detecting taps – this is due to the fact that it was easier to detect taps when the accelerometer readings were smoothed out as much as possible. To keep the integrity of the accelerometer readings, less filtering was done for the recorded data.

Once the Discovery Board has finished filtering all 10000 pairs, it is ready to transmit the data over UART to the Nucleo Board. As in the case with microphone data, the `Data Interrupt` pin is asserted. However, in this scenario, the `Mic Data` GPIO pin is reset – this way, the Nucleo knows that it is about to receive accelerometer data. Next, the pitch and roll are sent in consecutive UART transmissions. The Discovery first transmits the buffer of pitch data, and waits 10ms before transmitting the roll data. The 10ms delay allows time for the Nucleo Board to prepare for another UART reception.

After transmitting the accelerometer data, it will eventually be uploaded to the Web Server implemented for this project. However, in the case of accelerometer data transmission, the Discovery Board *does not* get a response. Thus, it returns immediately to the Idle state, where the system is ready to start all over again. At this point, no LED's should be illuminated.

2.2 Smart Phone Android Application

Given that the Nucleo board has no WiFi/Internet capabilities, data must be communicated over BLE to an Android application, that then forwards the data to the web server over HTTP. For convention, this report may use "Android app" to signify the smart phone BLE mobile application. The report also assumes that the reader has basic knowledge of telecommunication protocols, and Android applications. This portion of the report details the implementation and the rationale behind the design of the smart phone application that acts as the intermediary component between the Nucleo board and the web server.
With that being said, the requirements for the Android application are the following:

- Scan for and connect to BLE peripheral devices;

- Enable the user the ability to start, or stop scanning for devices, and connect or disconnect from one peripheral device;
- Discover BLE services and characteristics from the peripheral device;
- Read voice and accelerometer data batches over BLE from the Nucleo board;
- Save the received data to its appropriate file;
- Once the accelerometer file contains 10 seconds worth of data, transmit the file to the web server over HTTP;
- Once the voice file contains 1 second worth of data, transmit the file to the web server over HTTP;
- Handle HTTP responses from the web server and send data to the Nucleo board.

Each of the Android application's business-logic features are implemented in the Java programming language, and the user interface is designed in XML. The implementation of the Android application is facilitated by using the Android Studio IDE.

2.2.1 Brief Summary of Android

The report doesn't go into detail about the code written for the project, if the reader desires to see the source code themselves, they can see it here. There is documentation written within the code so that the reader may understand the basics of the code written. This report goes into detail about the high level designs and concepts used.

Android applications perform in a way such that all user interface and business-logic is performed within an *Activity*. Even if a developer doesn't need a user interface for their application, a main activity must instantiate and start once the user opens the application. Android developers must also declare any build dependencies such as programming libraries and hardware capabilities (such as Bluetooth and Internets) within the *manifest.xml* file. The activity, since there can be multiple activities, which runs on application start up is also declared in the manifest file.

2.2.2 BLE Interface

With regards to BLE, the smart phone is recognized as the *client device*, and the Nucleo board as the *server device*.

The first step for any BLE handshaking, is the *Scanning Phase*, which is facilitated by a *BLE Scan Callback*. For the client device to recognize BLE servers, the server must advertise itself and the client must scan for these advertisements. With the push of a *SCAN* button on the Android app user interface, the application enters a scanning mode which, by the help of a *Scan Callback* Java class, saves scanning results as MAC addresses that the Android application could try to connect to. Since scanning is cumbersome on the smart phone's battery, the scanning automatically stops after 10 seconds to save battery life. To facilitate full automation, the Android app automatically stops scanning once it finds the Nucleo board's MAC address and tries to connect to

the board. This improves the time required to enable a connection between the client and server since the user doesn't have to look through a list of MAC addresses to find the Nucleo board's address and have to select that specific address.

The last phase for the BLE handsaking is the connection phase, which is facilitated by a *GATT Client Callback*, where GATT stands for *General Attribute*. Once the Android app finds the Nucleo board, it automatically tries to connect to it, the GATT Client Callback takes charge of this operation. On the press of a CONNECT toggle button, the user can decide to connect or disconnect from the selected peripheral device.

The GATT Client Callback handles any connection events, and outputs statuses such as *Connection Success* and *Connection Failure*. Since there isn't any authentication procedure between client and server devices, the GATT Client Callback simply notifies the server that it wishes to connect to it and once the server, by the help of a GATT Server Callback, receives the notification, and responds with a connection success. If somehow the connection is a failure, the Android application simply logs the result to the Android Studio debug console. Although, on a connection success, the Android application now starts to search for *Services* that the server may be transmitting. If the service used to package voice and accelerometer data is discovered, and contains their appropriate *Characteristics*, the Android application is ready to read and be notified by any updates to the voice and accelerometer data.

At this point, the smart phone is connected to the Nucleo board over a BLE session and can now start to transmit data to one another! Exciting, if I do say so myself.

2.2.3 Handling Data

The Android app receives data in a byte array which is packaged under a characteristic assigned for either voice or accelerometer data. The batch of data is then written to its appropriate file with the help of the `AppController.java` class.

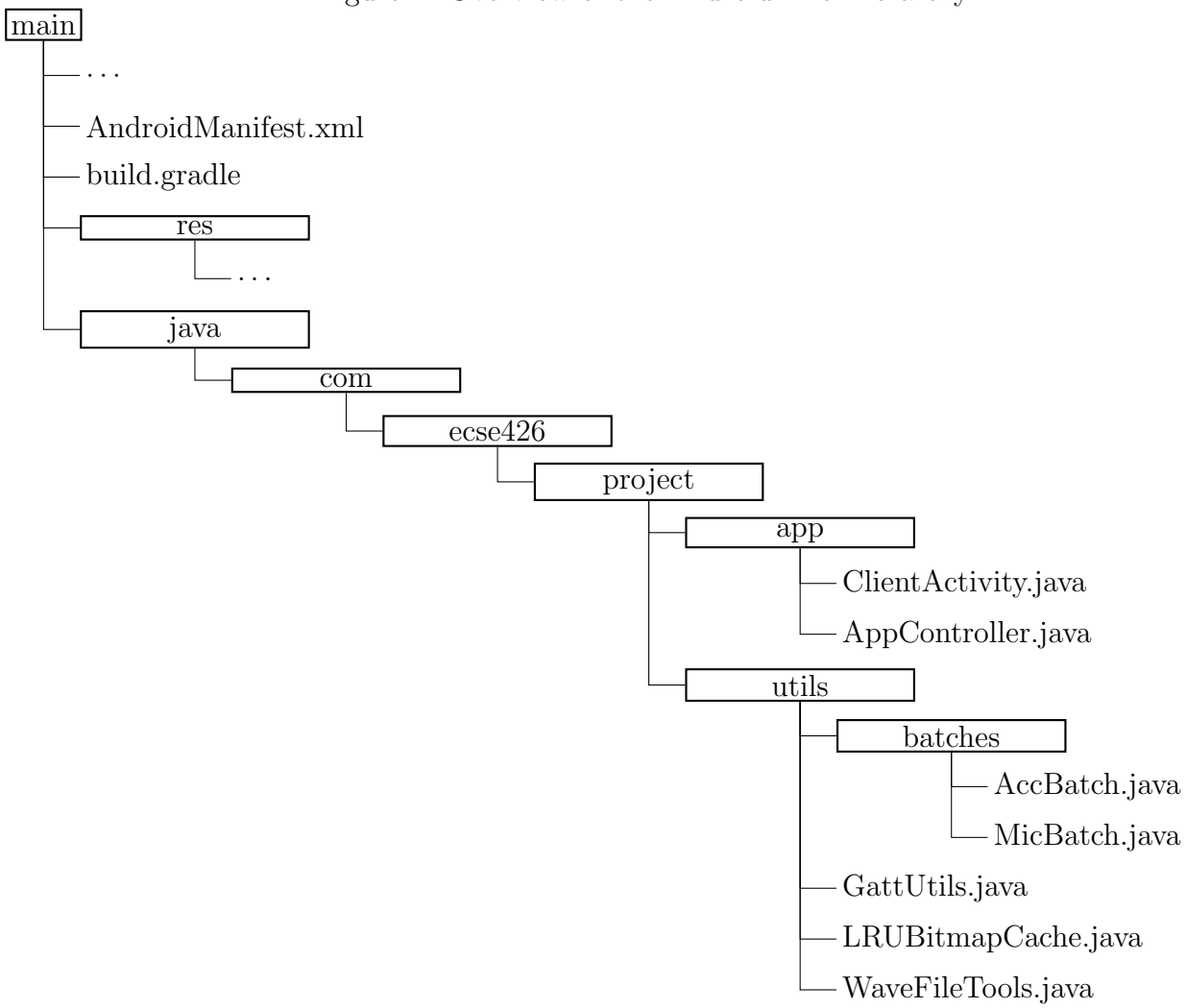
To send files over HTTP, the Android app makes use of the Volley Library to create and configure HTTP requests, while also handling any HTTP responses. This is useful if the developers wish to send files conveniently over HTTP as well as receive data from the web server over HTTP. The developers wished to keep data uploading simple. By encoding the file-to-be-sent into a base-64 string and adding the encoding to the HTTP request's form, the web server can easily retrieve the file from the request by reading and decoding the form body.

2.2.4 Summary of Project, Structure and Classes

One can see a visualization of the Android app project structure in Figure 2. Of course there are many files related to the application that couldn't be referenced under this report due to sizing constraints, any three dots represents that.

The `AndroidManifest.xml` is the manifest file specific to this application which contains dependencies. The `build.gradle` file is the gradle build script, Android Studio automatically runs its build configurations whenever the developer runs or builds the application.

Figure 2: Overview of the Android File Hierarchy



The `ClientActivity.java` class is the main activity that runs on start up. It is the core of the application, every other class is written around it and is used to help it. This class contains the BLE Scan Callback and GATT Client Callback logic implemented under inner classes. It handles user input and contains function calls from other classes that receive and save data over BLE and HTTP.

The `AppController.java` handles HTTP requests by facilitating the Client Activity with a queue for requests. It also handles reading and writing voice and accelerometer data to their appropriate files. It is important to note that the `AppController.java` class extends the Application class, making it able to run simultaneously with the `ClientActivity.java` class and have data persist when the application is closed.

The `AccBatch.java` and `MicBatch.java` classes are helper classes that contain functions to convert accelerometer or voice data respectively from bytes to a data type instructed by the function. The `GattUtils.java` class contains GATT Service, Characteristic, and Configuration UUIDs, as well as the Nucleo board's MAC address. The `WaveFileTools.java` class handles reading and writing data from and to files of Wave format. The `LRUBitmapCache.java` class is

supposed to send and receive files, unfortunately it is not used.

Under the `res` directory, one can find all the user interface layouts and images. Any user interface design or image is found under that directory.

2.3 The End of the Pipeline: A Convenient Web Server

In order to perform more complex data processing and to have somewhere convenient to store the recorded data, the web server was implemented. This was achieved with the use of Python's Flask library for creating a minimal HTTP server with a REST API and a nice, simple interface to visualize the data that it receives.

The server has two main API endpoints, one for each of accelerometer and microphone data. Thus, if the server is running on `151.155.209.95:48080`, the accelerometer endpoint is accessed via a `POST` request to `151.155.209.95:48080/accelerometer`, and the microphone endpoint is accessed via a `POST` request to `151.155.209.95:48080/speech`.

Flask manages API endpoints with a `Resource` interface. This interface provides `get()`, `post()`, and `put()` methods, which are called when the endpoint receives the corresponding HTTP packet. Thus, in the design of the web server, the `Accelerometer` and `Speech` classes were created that inherit from the `Resource` class.

2.3.1 The Accelerometer Endpoint

The `/accelerometer` endpoint accepts `POST` requests and is responsible for preprocessing accelerometer data, storing the data on the server, and plotting a graph of the data it receives. `POST` requests to this endpoint should have JSON bodies as described in Table 1. The API system is

Table 1: JSON format for `POST` requests to the `/accelerometer` endpoint

Parameter Name	Parameter Type	Description
"accelerometer"	`[float]`	List of accelerometer readings. Pitch values at even indices.
"starttime"	`String`	String indicating the time at which the recordings were sent to the API.

configured bind the `Accelerometer Resource` to the `/accelerometer` endpoint. As such, this `Resource` implements the `post()` method to handle the accelerometer data that it is sent via `HTTP POST`.

Since the "accelerometer" member of the `POST` request accepts an array of interleaved pitch and roll values, the data needs to be processed such that the pitch and roll could be stored in a more convenient format for plotting. The first task of this method is to parse the "accelerometer" member of the `POST` request to split up the pitch and roll data into their own respective lists. During this procedure, the data is written to the `data.csv` file on the server in comma-separated value (CSV) format. Each row of the CSV file contains a pitch reading and the corresponding roll reading. Furthermore, the "starttime" member of the `POST` is extracted and stored in a global variable

so it can later be inscribed on the user interface.

With the pitch and roll values split into their own lists, they can be graphed with relative ease. The powerful Matplotlib[3] library is used to plot the graph, and the pitch and roll data are both plotted in the same plane. The plot is saved to the `static/graph.png` file, and is then available to be rendered on the user interface.

Since the accelerometer communication is a one-way procedure, the `Accelerometer Resource` has nothing interesting to return to the device that sent the `POST` request. Thus, its response contains only an acknowledgement string.

2.3.2 The Speech Endpoint

Similarly to the accelerometer endpoint, implementation of the speech functionality on the web server required the construction of a `Speech Resource`, which was bound to the `/speech` endpoint. The files portion of the body of the `POST` requests that this endpoint expects is shown in Table 2.

With the WAV file extracted from the `POST` request, the task of the speech endpoint is to perform

Table 2: Format for `POST` request files sent to the `/speech` endpoint

Parameter Name	Parameter Type	Description
"audio"	WAV File	File containing audio recording in WAV format.

speech recognition. This is accomplished with the help of Google Cloud's Speech API. Fortunately, Google Cloud provides a Python interface for their fabulous speech recognition algorithms. The API's `transcribe_audio()` method is called on the WAV file, and a string is produced, containing the transcription of the audio recording. We try to cast this transcription to an integer, and if that fails we deduce that no number could be understood from the audio recording. In this scenario, we report a value of 0 in the `result` variable. Otherwise, `result` is assigned the number yielded by casting the transcription to `int`.

Contrarily to the case of the accelerometer endpoint, the microphone data communication process in this system is actually bidirectional. Thus, the sender of the microphone data expects a response from the web server, which will be passed all the way back to the Discovery board. The `Speech Resource`'s `post()` method returns a JSON object, which is illustrated in Table 3.

Table 3: JSON format for the response returned by the speech endpoint to `POST` requests

Parameter Name	Parameter Type	Description
"reading"	`int`	Byte containing the number transcribed from the input audio file. If no number is detected, 0 is returned.

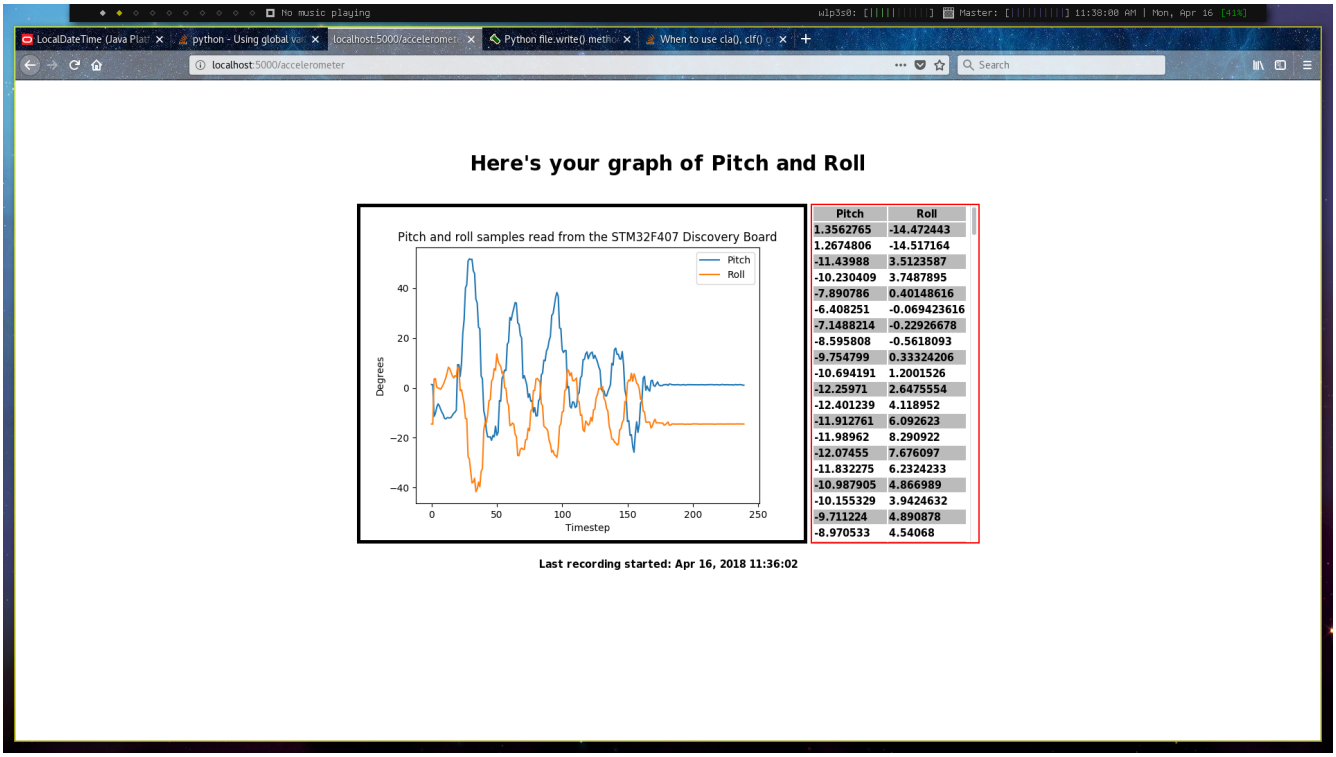
2.3.3 User Interface

A user interface was implemented in order to have a convenient way of visualizing the accelerometer data. This was designed as a web page hosted by the Flask server described above. To realize this web page, a simple HTML layout was created that exploits Flask's *template* functionality. Templates allow developers to dynamically pass parameters to HTML files – in this scenario, this was used to dynamically update the accelerometer data and recording time shown on the page.

To access the web page, whilst assuming the web server is running on `151.155.209.95:48080`, one would navigate to `151.155.209.95:48080/accelerometer` in their favorite web browser. The interface then displays the graph of the pitch and roll data, and shows the time at which the data was sent directly underneath the graph. Furthermore, the UI presents a scrolling table of the CSV data saved in `data.csv` for the user to peruse comfortably. A screenshot of this user interface is shown in Figure 3.

In order to view the latest data, one must just refresh the web page. The graph displayed

Figure 3: Screenshot of the web server's User Interface



Pitch	Roll
1.3562765	-14.472443
1.2674806	-14.517164
-11.43988	3.5123587
-10.230409	3.7487895
-7.890786	0.40148616
-6.408251	-0.069423616
-7.1488214	-0.22926678
-8.595808	-0.5618093
-9.754799	0.33324206
-10.694191	1.2001526
-12.25971	2.6475554
-12.401239	4.118952
-11.912761	6.092623
-11.98962	8.290922
-12.07455	7.676097
-11.832275	6.2324233
-10.987905	4.866989
-10.155329	3.9424632
-9.711224	4.890878
-8.970533	4.54068

on the user interface as well as the data used to generate the graph and the table shown are persisted on the server, so they can be viewed offline as well.

References

[1] F. Wortmann and K. Flüchter, "Internet of things," *Business & Information Systems Engineering*, vol. 57, no. 3, pp. 221–224, 2015.

[2] K. Sanders, *Ethics and Journalism*. Sage, 2003.

[3] J. D. Hunter, "Matplotlib: A 2d graphics environment," *Computing In Science & Engineering*, vol. 9, no. 3, pp. 90–95, 2007.

Appendices

Appendix A - Setting up the Web Server

Some minor setup is necessary in order to run the web server, however the process is drastically simplified when taking advantage of some serendipitous Python tools. Firstly, Python 3 will be required. Furthermore, it is recommended to use `virtualenv` to keep dependencies managed. Finally, this tutorial will be assuming the user has access to the free open-source Python package manager, `pip`.

Firstly, navigate to the `api/` directory in this project's root. It is strongly recommended to create a `virtualenv` here, but it is not necessary. Next, execute the following command:

```
$ pip install -r requirements.txt
```

This will install all Python package dependencies required for the project. With these dependencies installed, the server is ready to run! Execute the following command, still within the `api/` directory:

```
$ python api.py
```

The command above launches the web server on port 5000. The server will run indefinitely. When it is desired to kill the server, navigate to the shell through which the server is being run and press `CTRL + C`.

Note that for the end-to-end pipeline described in this paper, the Android application must be configured to send HTTP packets to the IP of the machine running this server. In order to do this, navigate to the file at:
`<project root>/android/app/src/main/java/com/ecse426/project/app/AppController.java`

In this file, edit the string `WEBSITE_ADDRESS` to contain the IP address of the machine running the server. For the changes to take effect, the Android app must be rebuilt and reinstalled on an Android device.